

AUTOMATED CARBON DIOXIDE CLEANING SYSTEM

**David T. Hoppe
NASA Marshall Space Flight Center
MSFC, AL 35812**

ABSTRACT

Solidified CO₂ pellets have been proven to be an effective blast media for the cleaning of a variety of materials. CO₂ is obtained from the waste gas streams generated from other manufacturing processes and therefore does not contribute to the green house effect, depletion of the ozone layer, or the environmental burden of hazardous waste disposal. The system is capable of removing as much as 90% of the contamination from a surface in one pass or to a high cleanliness level after multiple passes. Although the system is packaged and designed for manual hand held cleaning processes, the nozzle can easily be attached to the end effector of a robot for automated cleaning of predefined and known geometries. Specific tailoring of cleaning parameters are required to optimize the process for each individual geometry. Using optimum cleaning parameters the CO₂ systems were shown to be capable of cleaning to molecular levels below 0.7 mg/ft². The systems were effective for removing a variety of contaminants such as lubricating oils, cutting oils, grease, alcohol residue, biological films, and silicone. The system was effective on steel, aluminum, and carbon phenolic substrates.

INTRODUCTION

A high level of cleanliness is a typical requirement for the sensitive hardware routinely lifted into space. The fairings surrounding this equipment must be equally clean to prevent contamination of the payload. The high vacuum of space will cause even a minute amount of residual contamination to off gas and potentially redeposit on the payload compromising its intended service.

The high speed which space craft accelerate through the atmosphere can have a devastating effect on the ship's thin skin. The friction of the atmosphere causes severe erosion and elevated temperatures. The space craft is protected from this harsh environment by applying a coating of material designed to be eroded away during the flight called an ablator. This ablative material must adhere tightly to the surface of the space craft. If the ablator were to peel off during flight, the exposure to the space craft could greatly compromise the integrity of the vehicle. The level of cleanliness is also an important factor in adhesion strength and determines to a large extent the quality of the bond.

BACKGROUND

Most standard cleaning processes utilize a labor intensive manual effort and some require large amounts of environmentally hazardous and chemically dangerous cleaning agents. Typical processes include high pressure water spray, various soaps, vapor degreasing, mechanical grit blasting, aqueous solutions, and solvents such as Freon 113, methyl ethyl ketone, isopropyl alcohol, and methylene chloride. All of these processes generate more waste than the contamination being removed. Often this waste is considered hazardous and poses a potential threat to the environment. Many of the processes require personnel to wear extensive safety protective clothing. Some chemicals such as Freon 113 have a deleterious effect on the ozone layer. The Environmental Protection Agency (EPA) has imposed reduction requirements on the use of chlorofluorocarbon (CFC) compounds. Based on 1986 levels, the use of CFC's must be reduced by 50% by 1991 and eliminated by 2000.

Manual hand cleaning of components require a great deal of effort and time. Cleaning the first payload fairing of the Titan IV rocket required approximately 11,000 man hours. The processes used large quantities of Freon 113, hand wipes and cotton swabs. Hand cleaning often requires extensive cleanliness inspections and recleaning.

Clearly there is a need for a cleaning method which is radically different from those previously described. This process should greatly reduce the amount of hazardous waste generated in the existing procedures. The requirement for protective clothing and personal protection equipment should be reduced. The time involved in performing the cleaning operation should also be greatly reduced. The manpower level effort should be much lower. The process should be safe for the hardware being cleaned. The total costs due to reduction in manpower level, time expenditures, waste processing, and incorporating safety measures should be significantly reduced.

One cleaning method incorporating all these requirements was investigated in a joint venture between the USAF and NASA. The process uses a solidified CO₂ pellet media blast. This investigation was initiated by Martin Marietta Corporation (MMC) as an Industrial and Modernization Improvement Plan (IMIP) to demonstrate that the CO₂ blasting process could enhance the Titan IV Payload Fairing (PLF) cleaning process, reduce costs and meet the EPA requirements.

After an initial study of two separate CO₂ cleaning systems, one system was chosen for intensified studies and installed temporarily at MSFC. The second system was brought in later and used for a comparative study for use on cleaning components associated with the current space shuttle system and future advanced solid rocket motor materials. The CO₂ cleaning equipment and operator were provided by Environmental Alternatives. The two CO₂ cleaning systems were provided by Alpheus and Cold Jet.

CO₂ CLEANING

Process Description

Equipment

The CO₂ cleaning system is shown in figure 1. A tank stores liquid CO₂ at 200-300 psig. The pelletizer has a 2 step process. First the pelletizer transforms the liquid CO₂ into a snow like solid by quickly reducing the pressure. Next the snow is compressed and extruded into pellets approximately 1/4" in diameter and 1/2" long. By changing the size of the die, used to shape the pellets, a wide variety of pellet sizes can be achieved. The system must be shut down to change die sizes.

A compressed oil free air source at 400 psig is required. The air is cooled and dried. Humidity in the air source will cause condensation and freezing which will cause the pellets to stick together. In the Cold Jet cleaning system, the CO₂ pellets were mixed with this driver air at the pelletizer. The compressed air forces the pellets down a hose through the nozzle where they are sprayed on the test article. The Alpheus system propels the pellets to the nozzle at 40 psig and then mixes the pellets with the compressed air at the nozzle.

The motion of the nozzle was controlled by the end effector on a T3-776 Cincinnati Milacron robot with 6 degrees of freedom. The positional repeatability of the robot arm is ± 0.1 inches. Robot motion patterns could be saved and reloaded into memory later. Although the robot is equipped with a teach pendant, a graphical dynamic software system allowed for computer simulation of the hardware setup and offline programming. In this way the robot motion could be programmed and checked for interferences, processing time durations, and test article coverage without actually risking an unintended motion which might cause some damage to the robot or the test article. The robot was mounted on a track base and translation table and is equipped with a controller. This provided the robot with the additional freedom of lateral motion. The translation table controller was interfaced with the robot controller. The positional repeatability of the translation table was ± 0.2 inches. The robotic set up is shown in figure 2.

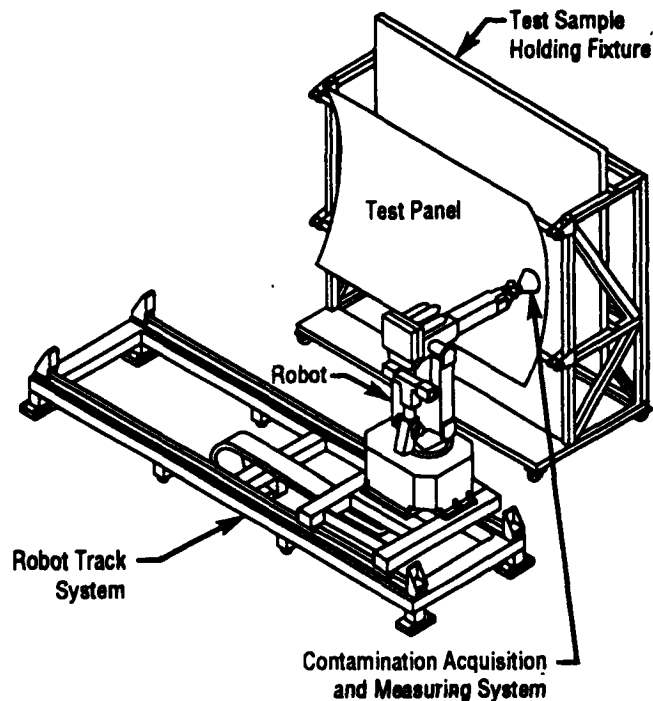


Figure 2 Robotic Setup

The robot and test article were housed in a portable class 100,000 clean room. A high volume contamination acquisition and filtering system was used to remove as much of the rebounding CO₂ gas with contamination from the area as possible. An accumulator housing was installed surrounding the nozzle to directly pull the gas away from the area. This system removed contamination from the clean room to minimize any redeposition of the contamination and was also connected to an experimental real time contamination monitoring system.

The real time contamination monitoring system consisted of a thermal quartz crystal microbalance for measuring molecular contamination and a laser particle counter instrumentation system for measuring particulate contamination. Results from the real time analysis systems would be compared to standard analysis procedures obtained by conventional methods performed in chemical analysis laboratories at MSFC, Martin Marietta laboratories at Manned Space Systems (Michoud) in New Orleans, Martin Marietta laboratories at Astronautics Group in Denver, South East Analysis Services Laboratories in Huntsville, AL, and Lockheed Laboratories in Sunnyvale, California.

Cleaning Process

The cleaning process has been recorded with high speed photographic equipment in order to observe the phenomena of the pellet impact on the substrate. It has not been possible to precisely determine the exact mechanics of the impact, but the cleaning effect appears to be due to a multimode transformation of the pellets. Contributing to the cleaning is the mechanical impact of the pellet as it strikes the substrate, a thermal shock to the contamination layer which embrittles the contamination making it easier to remove, sublimation of the pellet which results in a large volume expansion which blows the contamination away, and a possible momentary liquid phase which acts as a solvent. System parameters which influence the effectiveness of the cleaning process are clean room environment, humidity, nozzle translation speed, nozzle angle, system pressure and pellet mass flow rate, nozzle stand off distance, pellet density and size, the number of passes over the same area, the percent spray overlap per pass, contaminant being removed, and surface finish of the material being cleaned.

Cleaning Dynamics

Conventional grit blasting penetrates the contamination layer and actually removes a small quantity of substrate during the impact. The CO₂ pellet penetrates the contamination layer and sublimates on impact with the substrate. This phase change of the pellet dissipates the impact energy and causes no damage to the substrate. Very thin material may be blasted with the CO₂ pellets without causing any peening. The large volume change of the CO₂ during the sublimation helps to lift and blow the contamination from the surface resulting in cleaning a larger area per impact than grit. Direct contact with a pellet chills the neighboring area of contamination and weakens the bond to the substrate making the bond more fragile and easier to break. At very high pressures and mass flow rates, the pellets start to fracture as they near the surface, resulting in an increase in the number of impacts on the surface.

Wastes

All cleaning processes obviously result in waste from the contamination itself. Most processes also have a secondary waste from the cleaning agent. High pressure water spray will result in a large quantity of water which will require treatment and disposal of a concentrated sludge. Aqueous solutions although not harmful to the environment in themselves must be processed because of the entrained contamination cleaned from the substrate. Chemical solvents must be collected and stored as hazardous waste. Any hand wipes or cloths must also be handled as hazardous waste. The CO₂ cleaning system results in no secondary waste since the CO₂ pellets sublime and return to the atmosphere. The CO₂ used in the process is obtained from the waste gas stream from various other manufacturing processes and would have been exhausted to the atmosphere anyway.

Test Setup

Test panel configurations largely consisted of large flat plates, small 2" X 2" flatwise tensile test blocks, and complex geometries such as the isogrid pattern on the Titan IV payload fairing. Test panels were cleaned prior to the test with a conventional cleaning method and tested to assure that the contamination on the surface of the panel was less than 1 mg/ft². Known amounts of various contaminants were then applied to the surface of the panel. The panel was cleaned using the CO₂ cleaning system and the panel was again checked for cleanliness. Analysis utilized various standard techniques for determining non-volatile residue (NVR) and particles such as manual solvent flushes, tape lifts, optical scanning methods, and cloth wipes.

RESULTS

Titan IV Payload Fairing

Titan IV cleanliness requirements vary depending upon the payload being used. The most stringent requirements would be for a molecular contamination level of less than 1 mg/ft² and a particulate level under Visibly Clean Level 2. Visibly Clean Level 2 requires that the surface be free of all particles and oil films when observed by the unaided eye at a distance of 12-24 inches with 100-125 footcandles light intensity at the surface.

Tests performed were divided into three groups. The first group of tests was designed to identify the effectiveness of five different spray patterns in removing each of three different contaminants plus a mixture of all three contaminants. The second group of tests was designed to determine the number of times each spray pattern must be repeated in order to clean the test panel to the required degree of cleanliness. The third test was a validation of the most promising method while cleaning an actual 1/4 length section of a payload fairing.

The CO₂ cleaning system was proven to be an effective process for the cleaning of the payload fairing for the Titan IV rocket. It was determined from the first group of tests that a vertical nozzle motion was the most effective spray pattern. The second set of tests shows that most of the contamination is removed on the first pass since the upper layers of contamination are bonded to the lower layers and not to the metal surface itself. The

most effective nozzle orientation was proven to be one in which the nozzle is aimed in the direction of motion. This method blows the rebounding gas ahead of the nozzle and away from the previously cleaned section of panel.

The validation test utilized the most effective of the five spray patterns tested. The pattern consisted of a four pass vertical nozzle motion with a 50% spray overlap. The first pass held the nozzle perpendicular to the surface. The nozzle direction lagged its motion by 30° during the second pass and lead its motion by 30° during the third pass. These passes aid in cleaning around and behind obstructions. The fourth pass repeated the first perpendicular pattern. After the entire panel was cleaned, this entire process was repeated once more. The results show that the CO₂ cleaning system is capable of meeting the Titan IV requirements. Due to the geometry of the isogrid, some areas of the panel were obstructed by 4" deep stringers. Final NVR values averaged below 0.2 mg/ft² in both obstructed and unobstructed areas of the isogrid.

The experimental real time contamination monitoring system data showed the approximate trends in cleanliness level as the standard NVR Freon rinse tests but there was insufficient data to correlate the results and develop an equation.

Shuttle External Tank

CO₂ cleaning for use in preparing the shuttle external tank for ablator bonding was evaluated by bonding an ablative material to materials cleaned by either the CO₂ system or conventional chemicals. Various adhesion tests were conducted to compare the effectiveness of the CO₂ cleaning system to the standard process. The difference between the adhesive strength of the CO₂ cleaning system varied within ±10% of the adhesive strength of the panel cleaned by chemical processes.

Biological Film Removal

Microscopic biological organisms grown on metallic test slides have proven difficult to remove due to their tight bond with the metallic surface. In the past, slide have either been soaked in acid, and scrubbed and scraped with limited success, or simply discarded. Multiple passes of high intensity CO₂ pellet cleaning was able to remove the film from these slides to a much greater degree than any other method attempted. After cleaning the slides were etched so that the organisms would show luminously under a microscope. Clean and unclean areas of the slide could be compared side by side. The clean side showed almost no luminous areas.

Additional Testing

The system was demonstrated and tested on many other articles. It was shown that the CO₂ system is capable of stripping coatings as well as performing cleaning. Dry film lubricants were easily removed from nut bearings. Various thermal protective coatings and ablators were striped from aluminum test panels. By using special nozzles which fracture the pellets as they exit the nozzle, printed circuit boards were cleaned to remove the flux left on the surface after manufacturing.

Both Cleanliness and bonding test were conducted on ASRM candidate materials. 2" X 2" painted steel plates were cleaned with conventional cleaning agents and the CO₂ system. Test blocks were bonded to the cleaned surface which were then subjected to a flatwise tensile load. In all tests the failure occurred in other areas other than the cleaned surface bond indicating the CO₂ system is as effective as conventional cleaning procedures.

Various other steel, aluminum, and carbon phenolic materials were also cleaned. In all cases final NVR readings were in the low mg/ft² reading. It was determined that the contamination evacuation system and clean room environment were important factors in preventing the redeposition of contaminants after cleaning. During long blasting operations, the CO₂ pellet temperature could lower the test article temperature sufficiently to cause condensation. This condensation could result in flash corrosion. As the water droplets attach to the substrate they also bring with them other contaminants which are left on the surface after the water evaporates. It is

important that this condensation be eliminated to ensure a high level of cleanliness is maintained. New generation CO₂ cleaning systems are designed to slightly reheat and dry the test article in order to prevent the formation of condensation.

CONCLUSION

CO₂ cleaning systems are an effective cleaning system for the removal of many types of contamination on a wide variety of materials. The system is safe for use on even extremely thin materials, not hazardous, and not toxic. It is capable of meeting the goal of reducing the CFC usage per EPA requirements. The system is capable of quickly removing gross contamination and can be fine tuned to achieve a high level of cleanliness. Parameter optimization is required for each geometry although general patterns exist to provide a good starting point for any testing. With proper contamination evacuation, humidity control, and clean room environment it is possible to achieve NVR levels below 0.1 mg/ft².

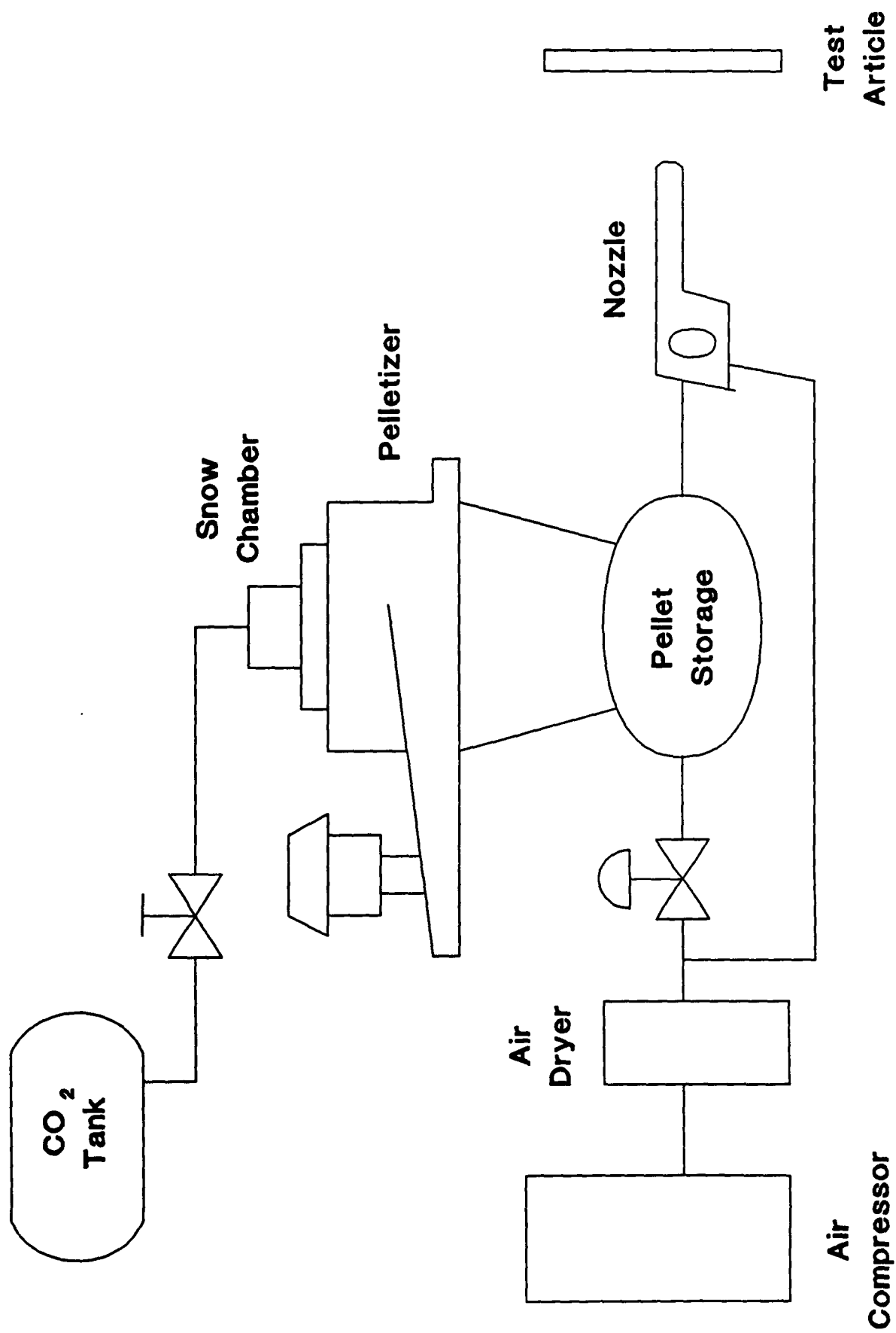


Figure 1: CO₂ Cleaning System Setup

MATERIALS SCIENCE

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